Narrow Angle Astrometry

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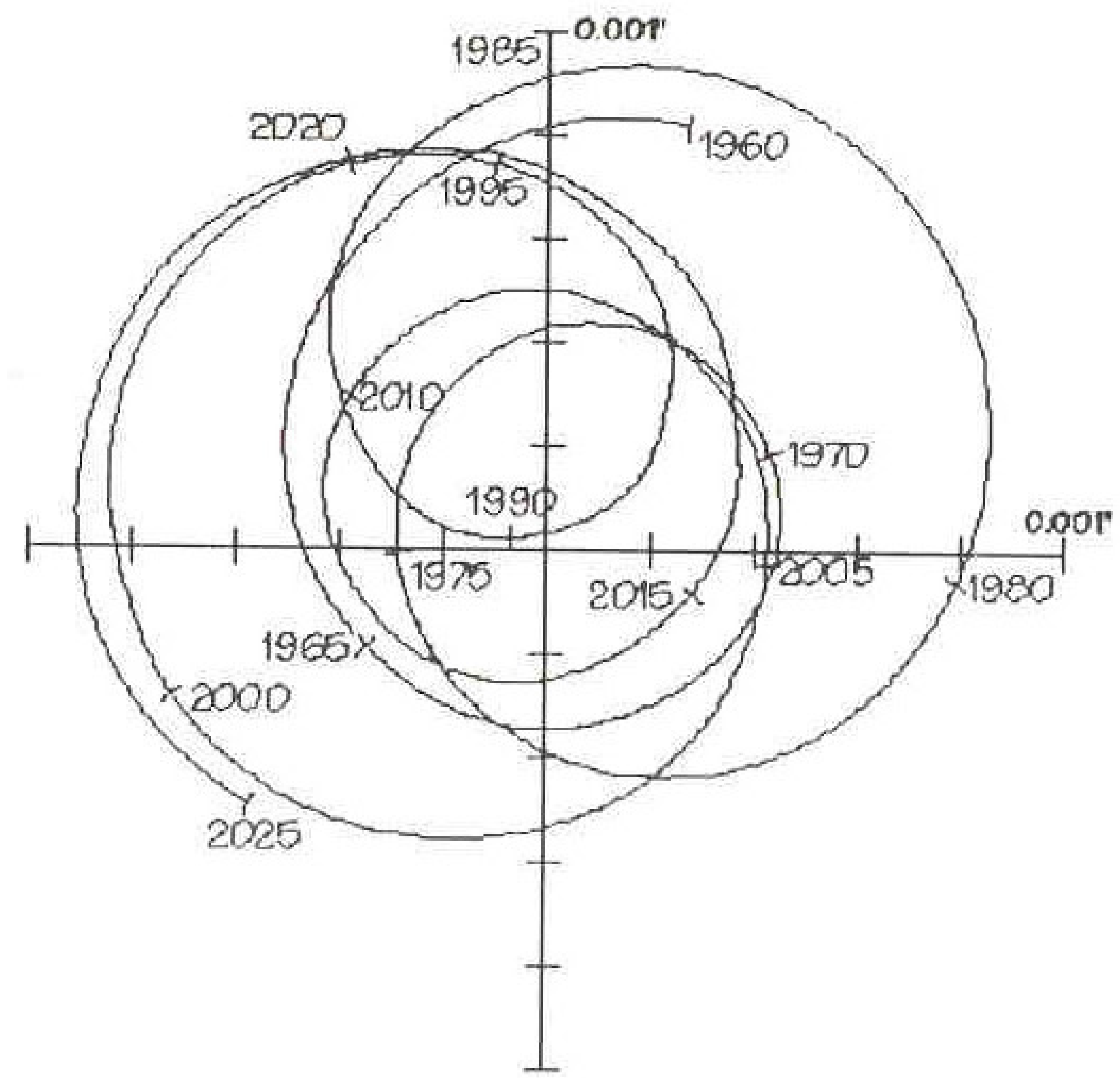
Looking for planets with narrow-angle astrometry

- Astrometry is a complementary technique to the radial velocity method
  - Senses transverse motion
  - Gives mass unambiguously
  - Jupiter - Sun = +/- 0.5 mas at 10 pc
- Needed accuracy to conduct an interesting search
  - < 50-100 uas
- Features of the problem
  - Fundamentally narrow angle
    - » Can use angularly-nearby references



Astrometric Signature

planet mass

$$\theta = \frac{m}{M}\,\frac{r}{L}$$

orbital radius

system distance

star mass

$$= \frac{m}{M^{2/3}}\,\frac{P^{2/3}}{L}$$

period

- mass ratio determined unambiguously
- signature $\propto 1/L$
- astrometry most sensitive to
    - large orbital radii
    - long periods

Types of measurements

- For describing atmospheric effects, it's useful to separate measurements into three categories
  - Wide-angle (10's of degree fields)
    - Transit instruments, optical interferometers
  - Traditional narrow-angle (0.1 - 1.0 degree fields)
    - Telescopes with CCD or Ronchi-ruling back-ends
  - Very-narrow-angle (< 0.1 degree fields)
    - Long-baseline IR interferometers
- General comments
  - Atmospheric effects decrease (non-linearly) with the size of the field
  - Over small fields, atmospheric effects also decrease with baseline length (telescope diameter)

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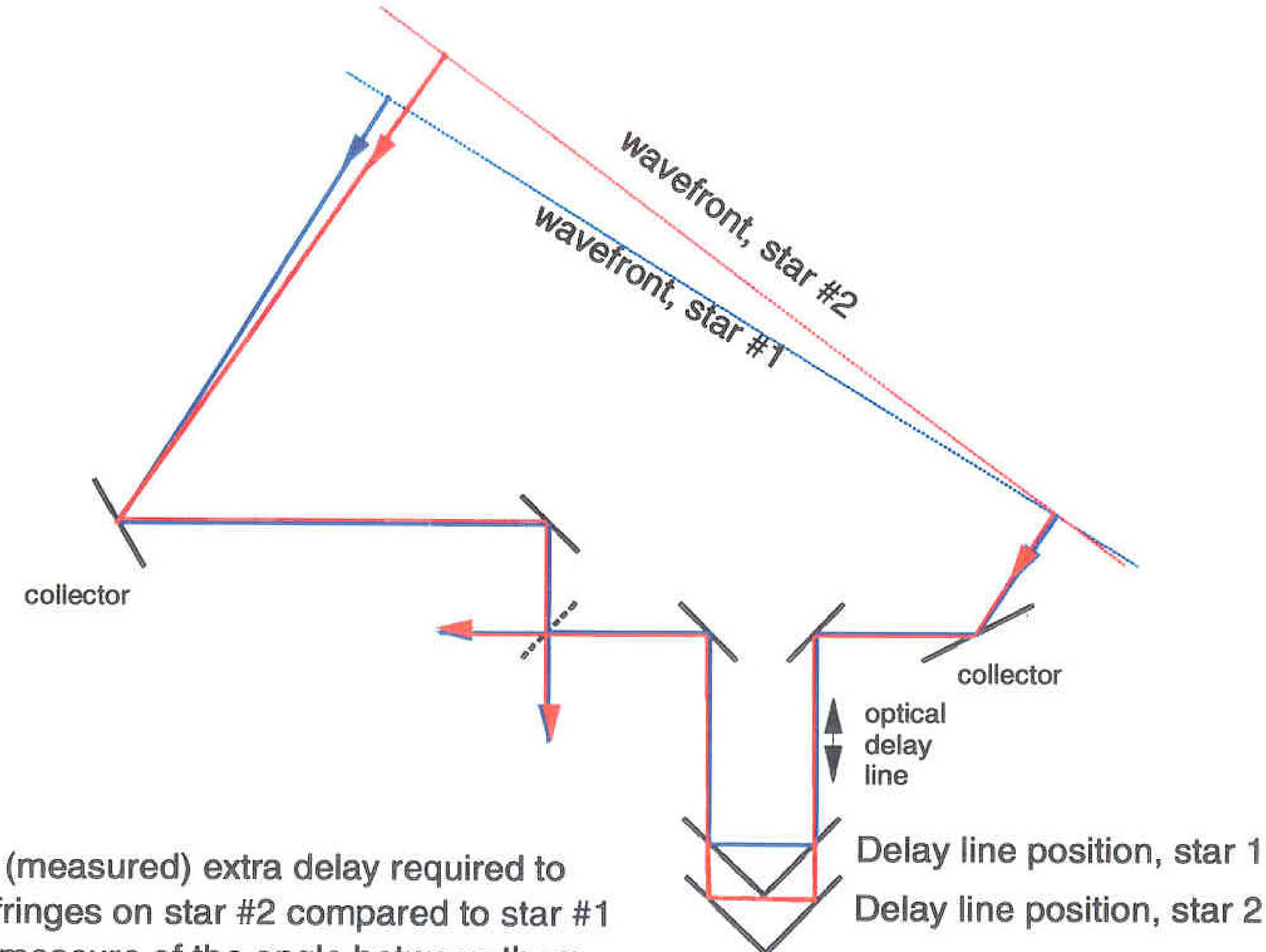
- 1) Fringe position tells us about position of source:

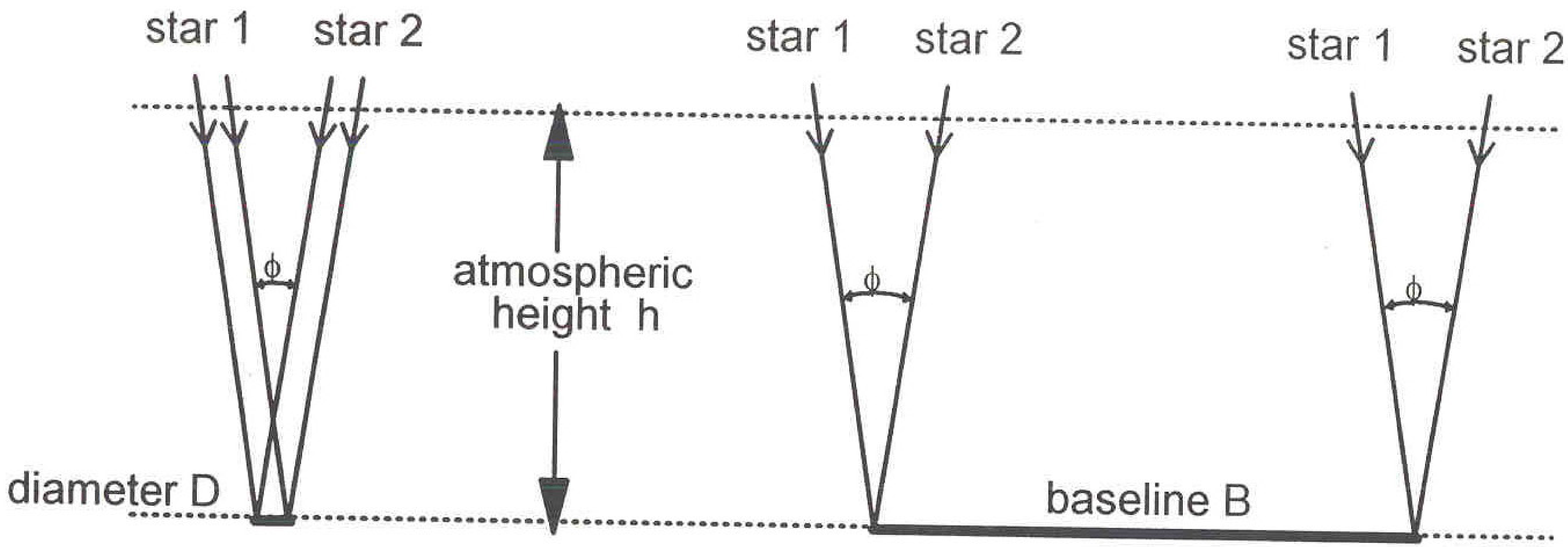
Astrometry with an interferometer



The (measured) extra delay required to get fringes on star #2 compared to star #1 is a measure of the angle between them

Atmospheric limitations to ground astrometry

- What is the source of the error in a differential measurement?
  - Light from each star follows different paths through the atmosphere
  - E.g., 10 km up in the atmosphere, the rays from two stars 0.5 degrees apart are separated by 100 m
    - ordinarily, >> diameter of the telescope
- Performance improves as the overlap of the beams increases
  - Increased telescope diameter or baseline length
  - Decreased star separation

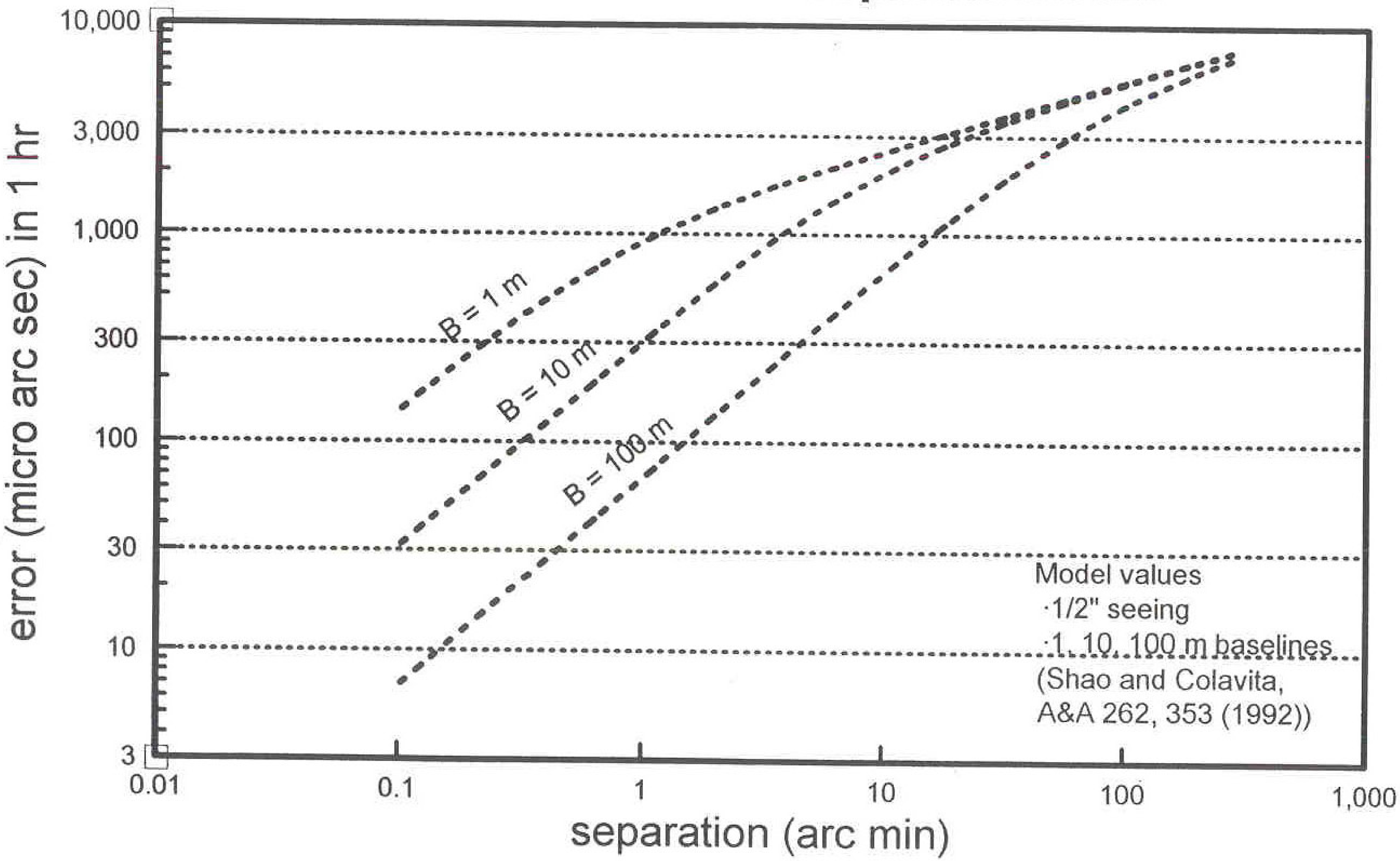


Traditional Narrow-Angle Regime
$\phi >> D$
error independent of D
error weakly dependent on ϕ

Very-Narrow-Angle Regime
$\phi h < B$
error decreases with increasing B
error linearly dependent on ϕ

Atmospheric Limit for a Differential Measurement

Predictions of Atmospheric Model



What about outer scale?

- Measurements at the Keck Observatory as part of the seeing campaign for the adaptive optics programs find a very small outer scale
  - Image motion (tip & tilt) is 3 - 4 times smaller than predicted based on an infinite outer scale; sufficiently small that a separate tip-tilt AO system at Keck was canceled
- Outer scale estimated from the correlation of the centroids of individual segments is 30-50 m
- Finite outer scale improves the narrow-angle astrometric results as $(B/(L0/2\pi))^{1/3}$

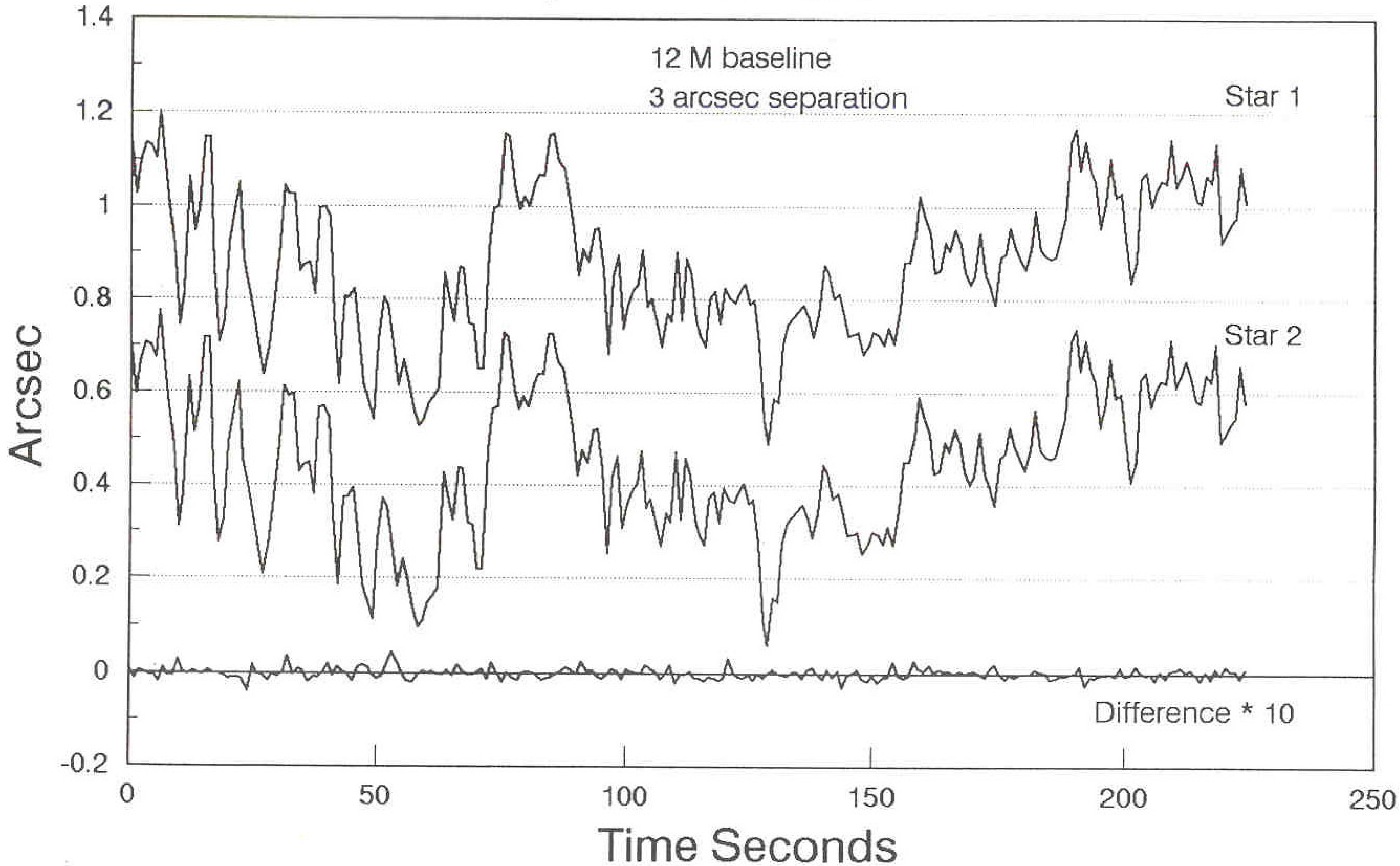
	infinite outer scale	40-m outer scale
B = 100 m, θ = 20 arc sec	21 uas-hr^1/2	8 uas-hr^1/2
B = 200 m, θ = 15 arc sec	10 uas-hr^1/2	3 uas-hr^1/2

Observational data in the very-narrow-angle regime

- There has not been much experimental data in this regime, so a series of measurements were made using the Mark III Interferometer to generate at least one data point
- The Mark III was modified to incorporate a split pupil with separate delays and detectors
- The subpupils observed the phase of the fringe packets from the primary and secondary of the 3.3" binary αGem

Mark III Differential Astrometry

Alpha Gem 12/92



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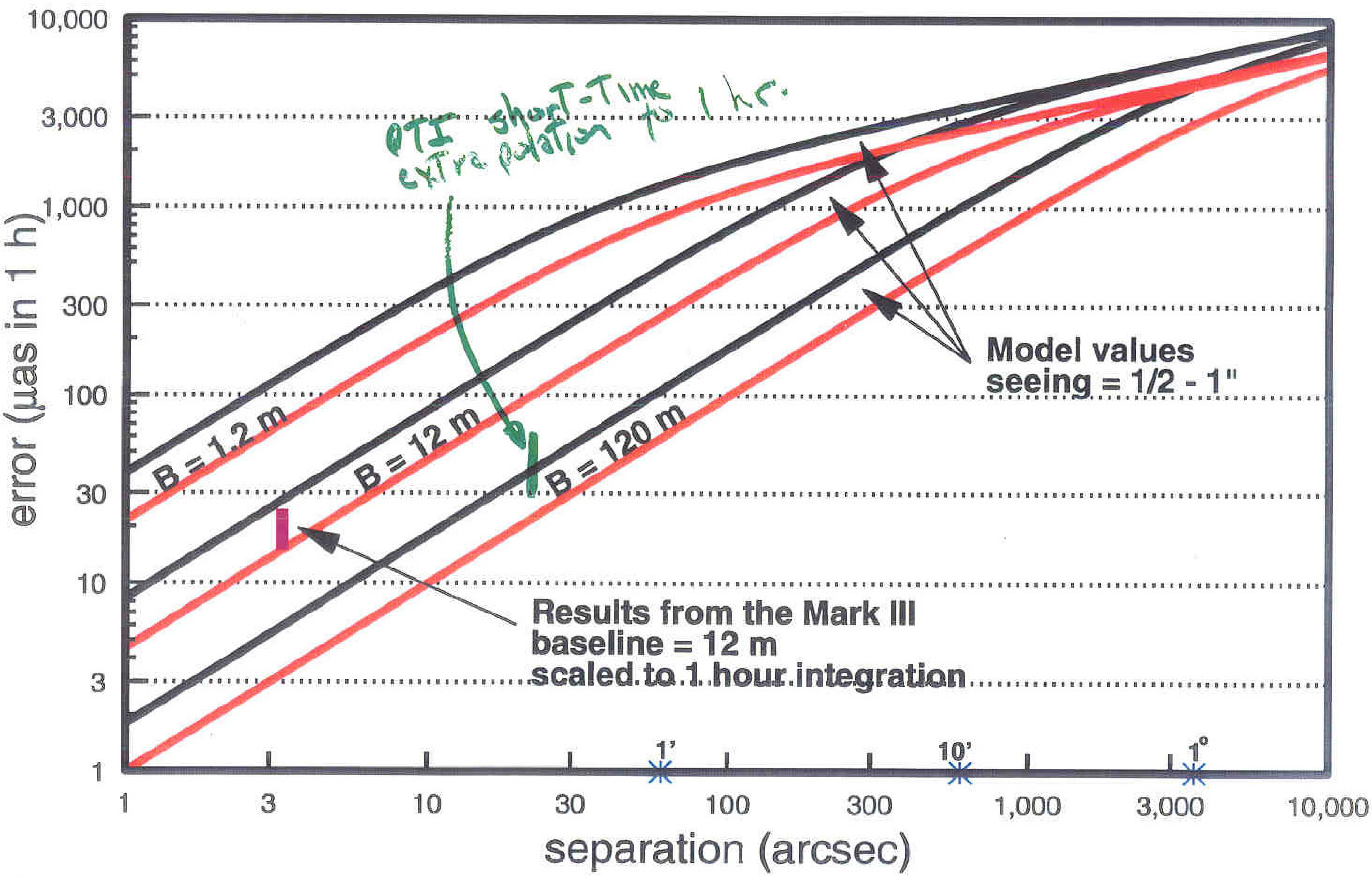
Atmospheric limits to a narrow-angle measurement



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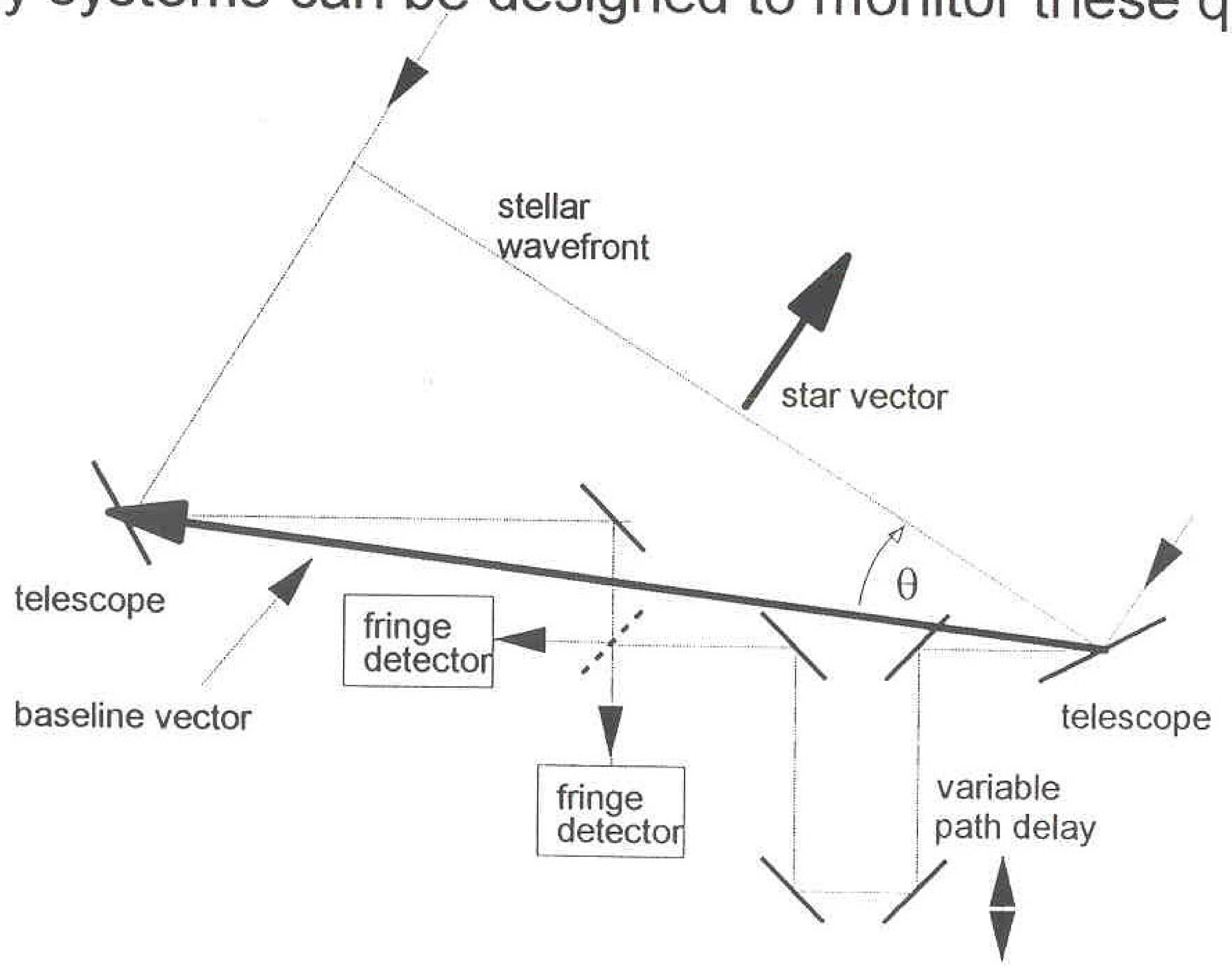
Implementation dual-star astrometry, I

- Two interferometers, sharing common baseline and apertures
- Laser metrology to “tie” the two interferometers together
- “Loose” tolerance on baseline knowledge because of small sky separation

Implementation

- Optical interferometers are good instruments to achieve the ultimate atmospheric limit
- Long baselines allow for better control of systematic errors
- Instrument geometry is described by 4 parameters: the baseline vector and the zero point of the delay measurement
  - Metrology systems can be designed to monitor these quantities



Sources of Error in a measurement

$$\text{delay} = B \cdot s$$

- estimate delay as

$$d = l + \frac{\lambda}{2\pi}\phi$$

fringe phase

laser position

- let angle $\theta \simeq d/B$

$$\delta\theta = \underbrace{\frac{\delta l}{B}}_{\text{systematic metrology errors}} + \underbrace{\frac{\lambda}{2\pi}\frac{\delta\phi}{B}}_{\text{SNR effects}} - \underbrace{\frac{\delta B}{B}\theta}_{\text{Baseline errors}} + \underbrace{\frac{a}{B}}_{\text{Atmospheric noise}}$$

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Effect of baseline length on astrometry

- Longer baselines help
  - Given linear metrology with accuracy **x**
    - » Astrometric accuracy scales as **x / B**
  - For a given number of photons, **N**, astrometric accuracy is given by

$$\sigma_\theta = \frac{1}{2\pi}\frac{\lambda}{B}\frac{1}{\sqrt{N/2V}}$$

Errors in The Baseline

- For wide-angle measurements, need to know baseline to same accuracy as desired astrometry

- But, if perform measurement over field-of-view (FOV) = θ, required baseline accuracy reduced by $\frac{1}{\theta}$

Ex:

<u>wide angle</u> $\epsilon = 10\,\mu as$ for $B = 100\,m$

must know B to 5 nm

<u>narrow angle</u> $\epsilon = 10\,\mu as$ for $B = 100\,m$ over a $20''$ (10^{-4} rad) field

must know B to $50\,\mu m$

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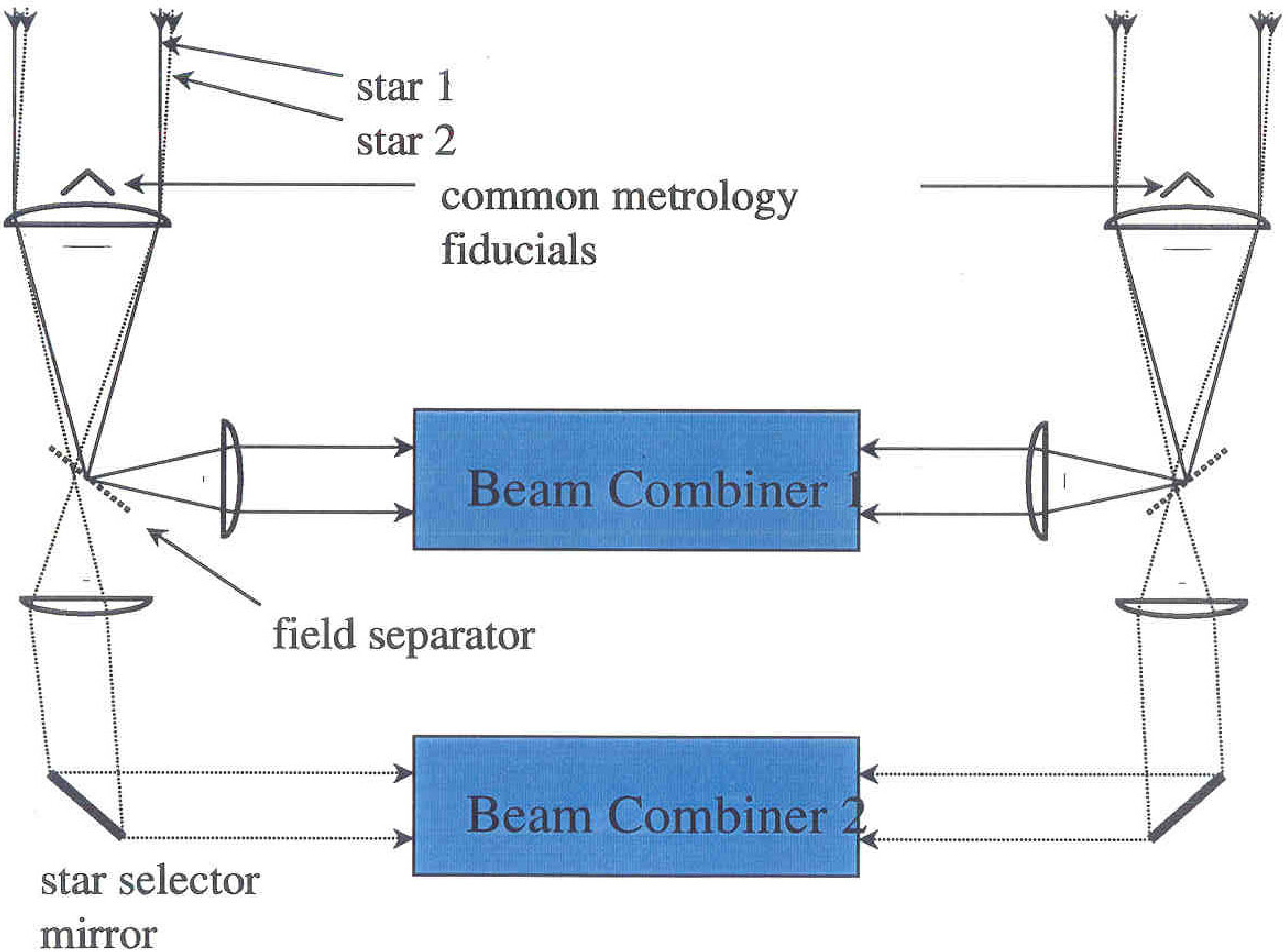
Dual-star concept



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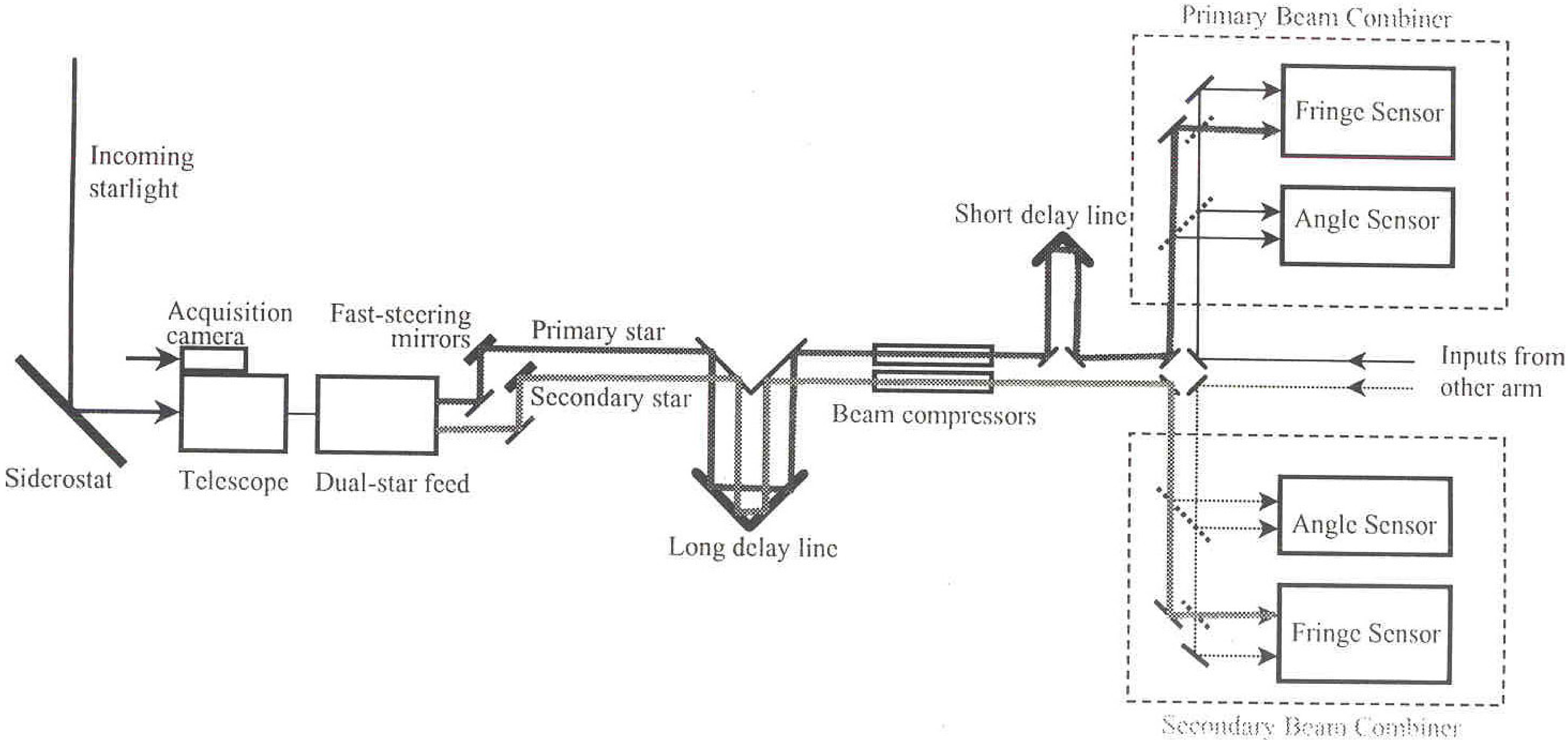
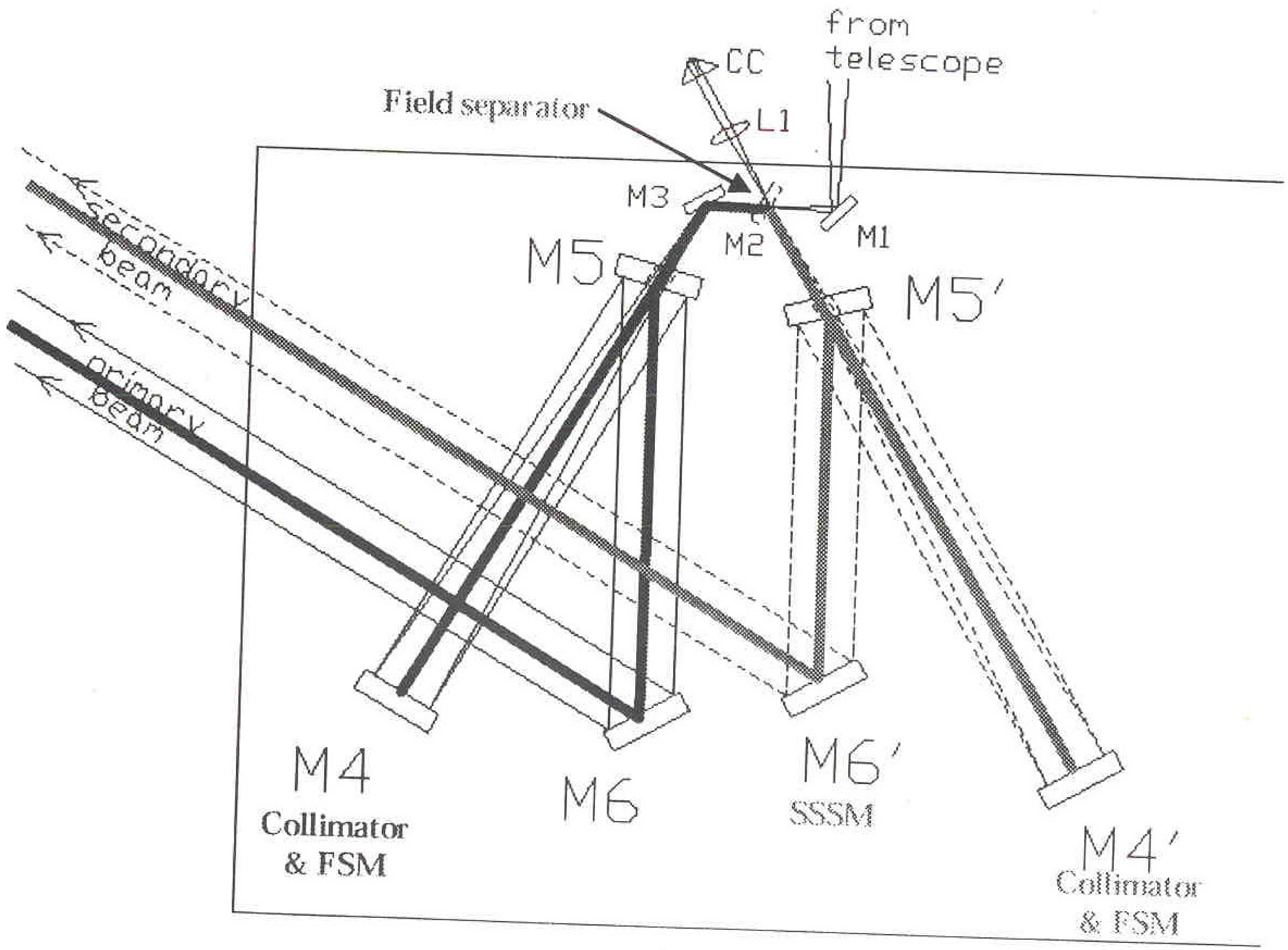
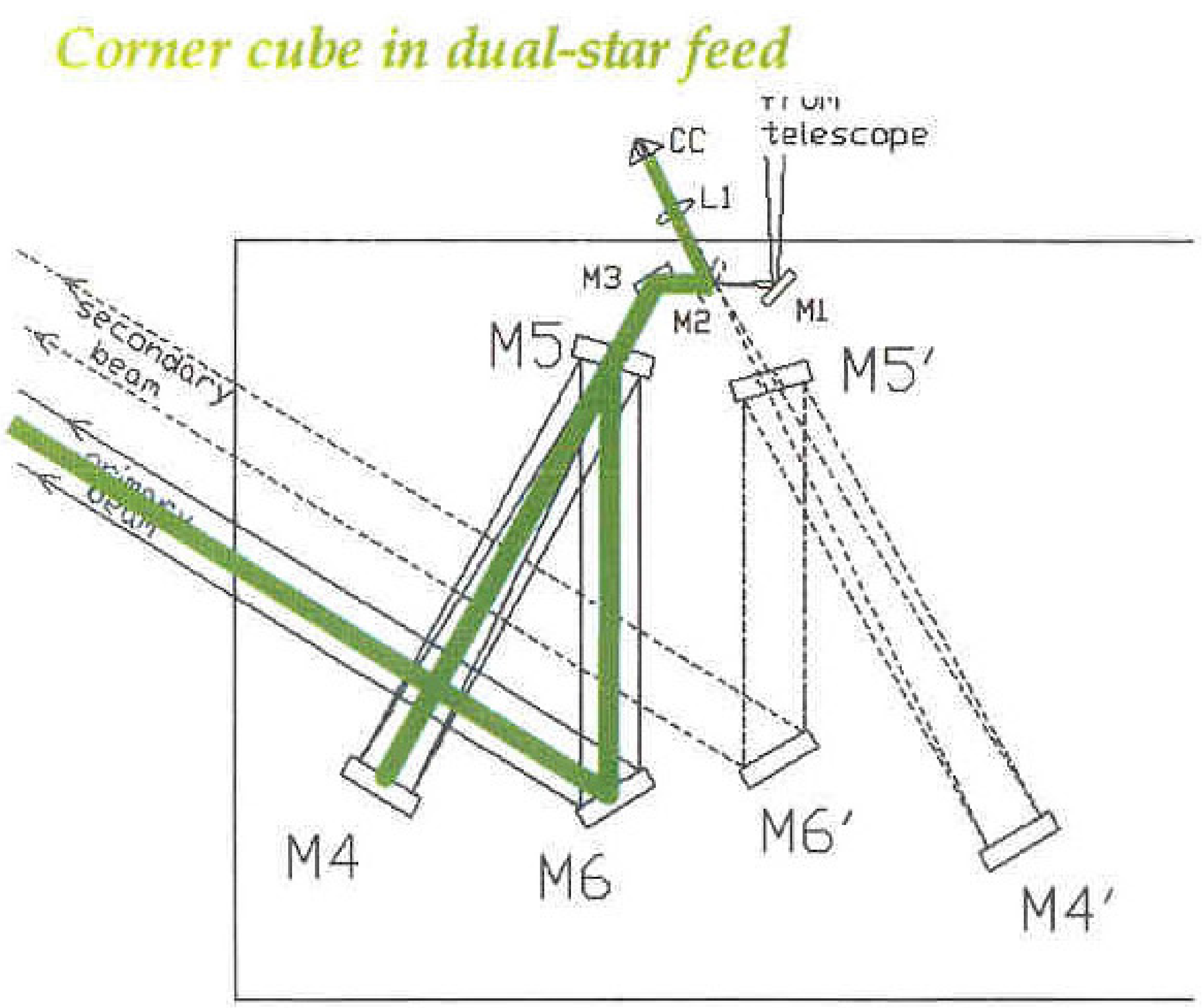
PTI block diagram

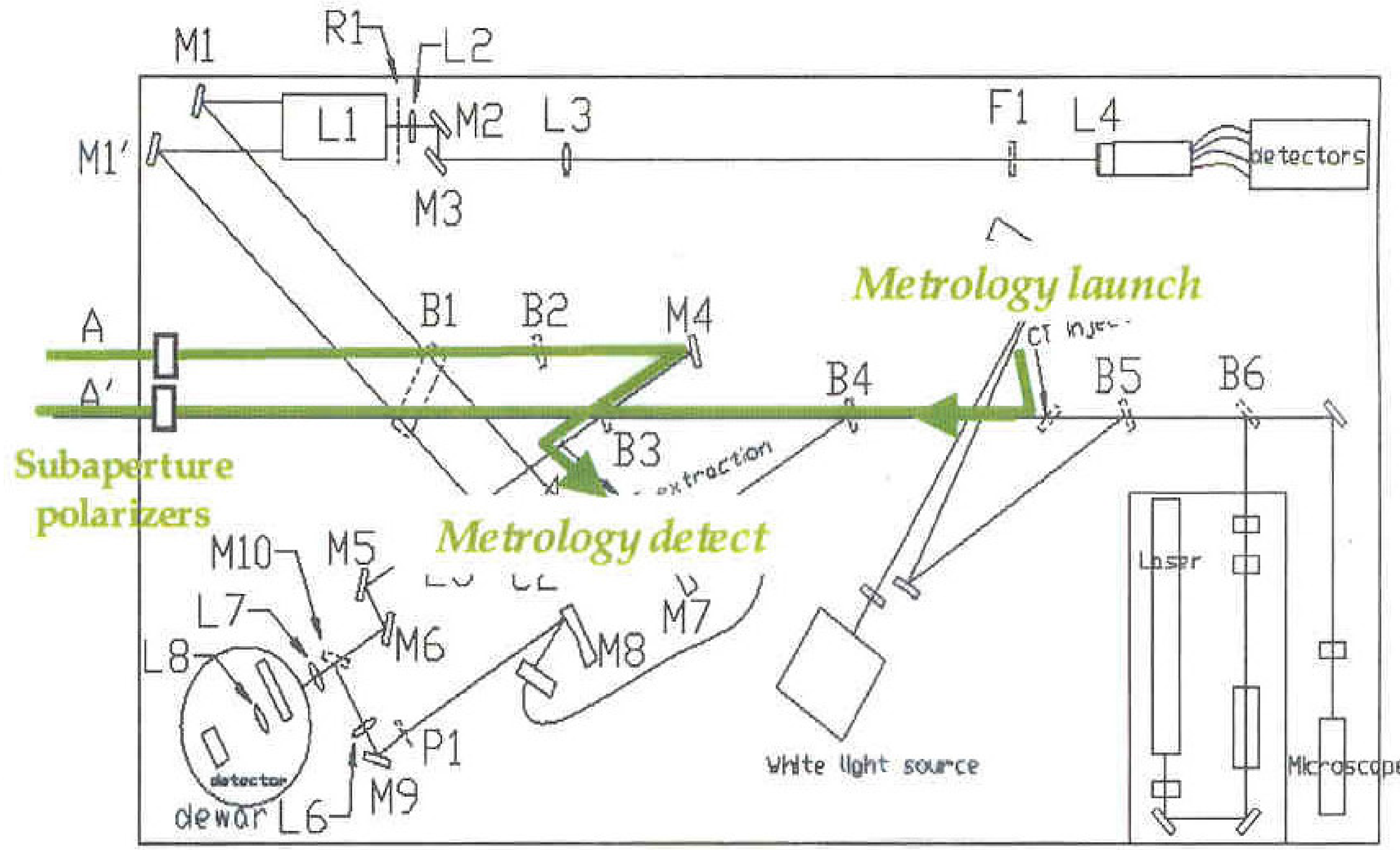


Dual-star feed



Constant-term metrology





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Phase referencing

- Similar to use of guide interferometers to phase SIM
- Like AO
  - AO uses a reference star (or laser guide star) to measure atmospheric wavefront distortions
  - Uses deformable mirror to correct distortion on reference star and in vicinity of reference star
- Phase referencing
  - Uses reference star (no laser tricks, unfortunately) to measure atmospheric fringe motion
  - Uses optical delay line to correct motion on reference star and in vicinity of reference star
- How is “vicinity” parameterized?

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Isoplanatic angle

- Vicinity of == in the same isoplanatic patch
  - Within the isoplanatic patch, the atmospheric effects on the stars are correlated
  - Isoplanatic angle = radius of isoplanatic patch
    - » $\theta_0 \sim 0.2 r_0 / L$, where L = "height" of turbulence
  - Also grows with wavelength...

Seeing	θ_0 at 0.55 um	θ_0 at 2.2 um
1 arcsec	2 arcsec	10 arcsec
0.5 arcsec	4 arcsec	20 arcsec

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Implementation dual-star astrometry, II

- Two interferometers, sharing common baseline and apertures
- Two stars: one bright (target w/planet, nearby); one faint (reference w/ no planet (hopefully), far away)
- Use target star as phase reference
  - Cophase (==phase reference) interferometer for stars within isoplanatic patch
- Chose reference star within isoplanatic patch of target star
- Work in the infrared (2.2 um) for its larger isoplanatic angle
  - Increases solid angle over which to find reference stars (15-20 arcsec radius)
  - Allows use of larger apertures (1.5--2.0 m with tip/tilt correction) to increase sensitivity
- Potential accuracy with 100-m baseline is 10's uas in an hour

Other issues, cont.

- Number of reference stars
  - For planet detection, two reference stars are needed to separate perturbations in the references from planetary signatures
- Chromatic effects
  - Compared to visible astrometry, atmosphere is 20x less dispersive and effective wavelength is a much weaker function of star temperature
- Metrology requirements
  - 10 uas at 100 m requires metrology of optical path to < 5 nm
    - Within current state-of-practice

Astrometry systematics error budget

		nm per arm	nm total	uas total
unmodeled pivot noise	25.0 um	1.9	2.7	5.5
pivot beacon to pivot transfer	25.0 um	1.9	2.7	5.5
DSM CC to beacon transfer	25.0 um	1.9	2.7	5.5
baseline solution	35.0 um		2.6	5.4
DCR				5.0
beamwalk of secondary over field		2.5	3.5	7.3
alignment of metrology to starlight	0.5 arc sec	1.8	2.5	5.2
alignment drift	0.5 arc sec	1.8	2.5	5.2
metrology stability	1.00E-08 fractional	0.1	0.1	0.2
metrology polarizer mount gradient	0.04 K	2.0	2.8	5.8
fringe-measurement accuracy	0.005 rads	1.8	2.5	5.1
beamwalk stability in propagation	1.5 mm	2.3	3.2	6.6
			TOTAL:	**18.8 uas**

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Astrometry Observation

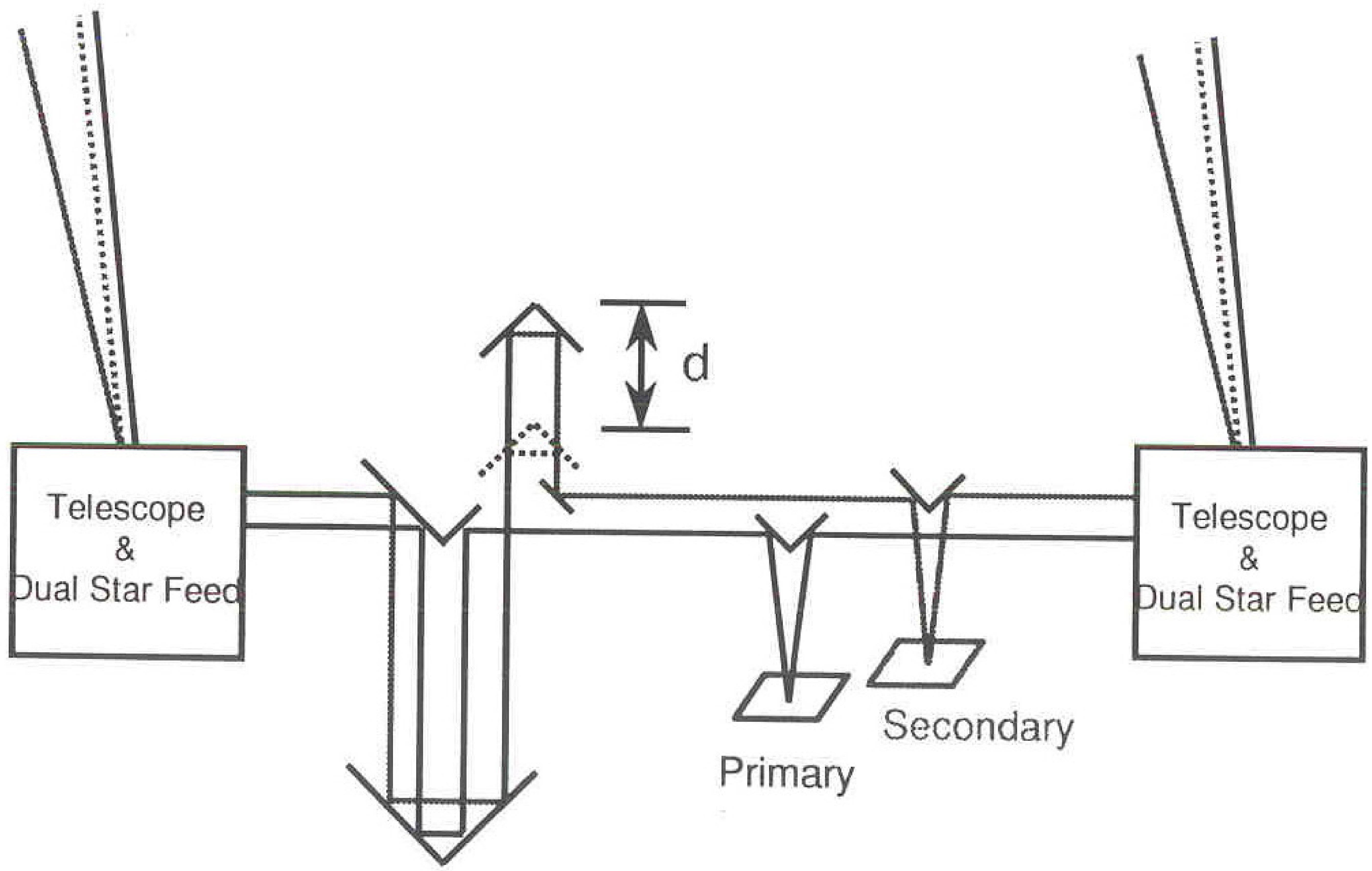
Primary Combiner

Track Primary Star

Secondary Combiner
(chops between primary and secondary)

Track Primary Star | Track Secondary Star | Track Primary Star | repeat...

Making a narrow-angle measurement



Differential delay line shown in secondary path for clarity

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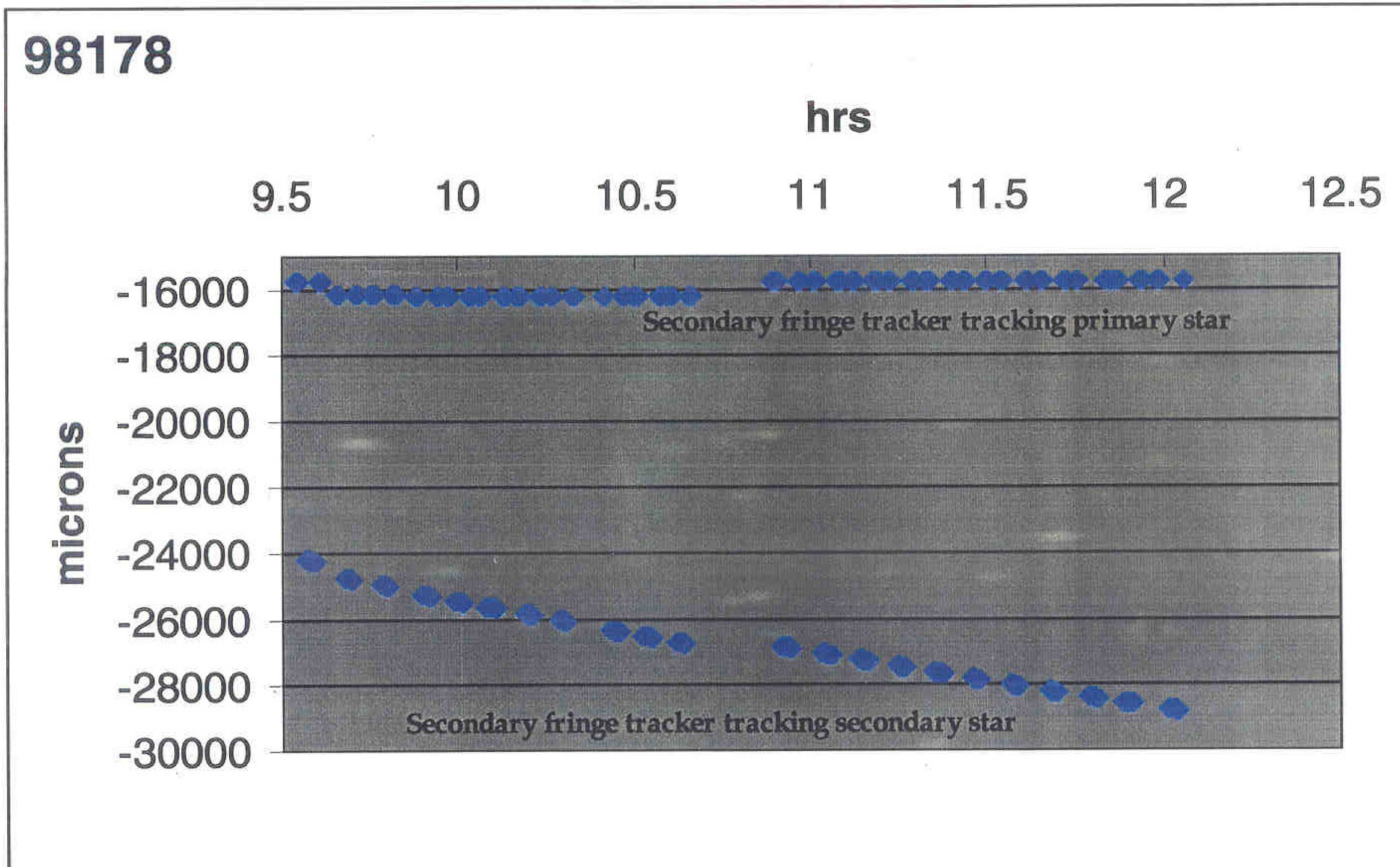
Raw data after outlier removal



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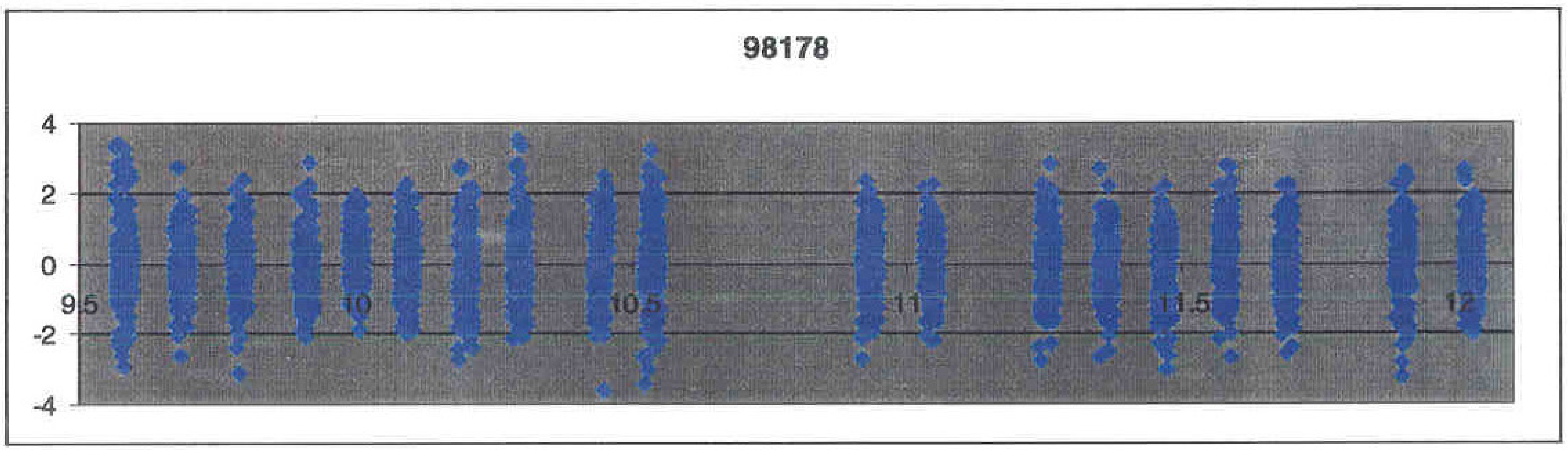
Calibrated data, 0.5-s per point



After removal of best-fit sin, cos, and constant

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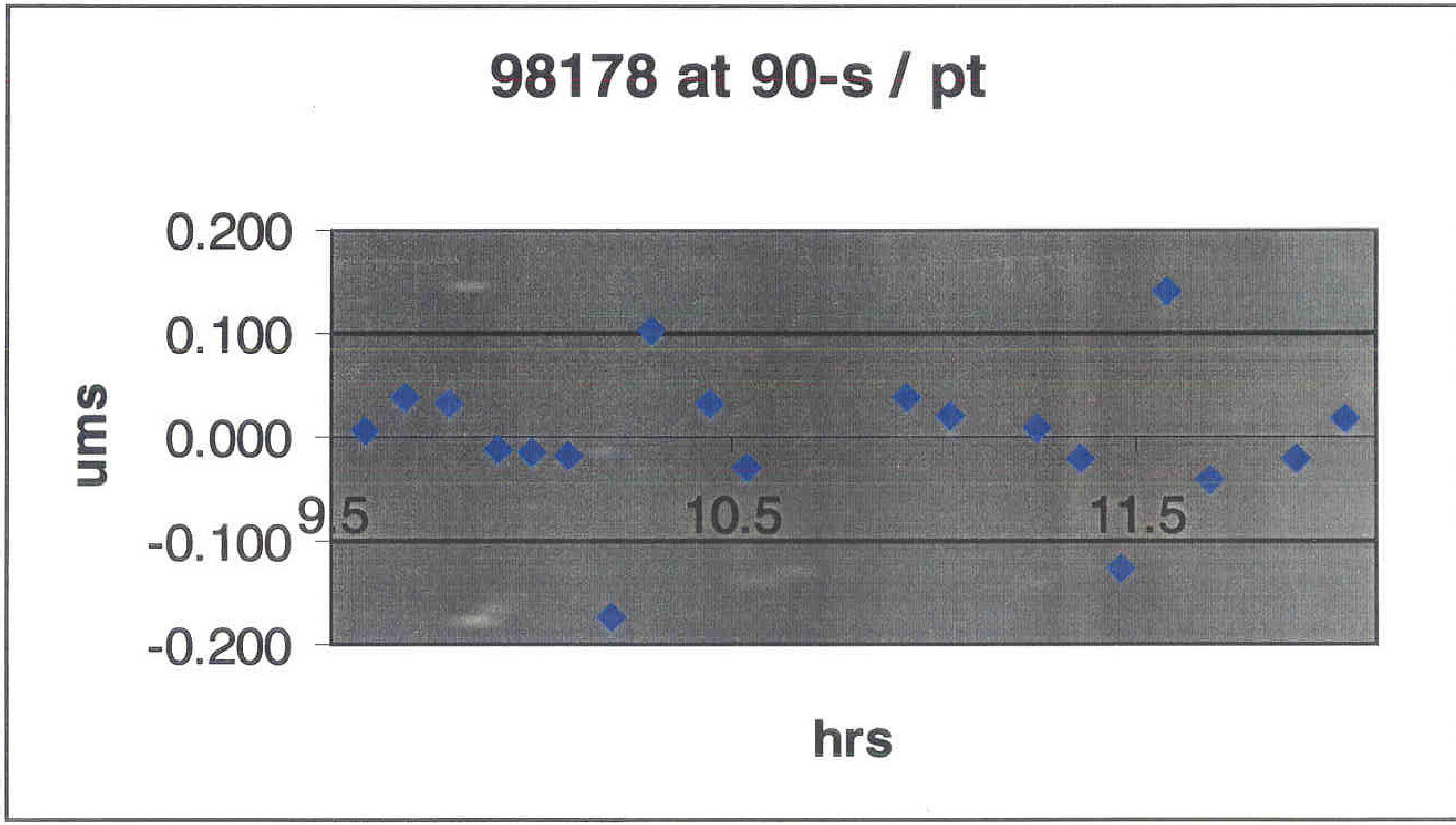
Averaged data



Internal errors: 70 nm rms; 140 uas rms per 90-sec point